

THE YOUNG VOLCANIC REGIONS OF SOUTHEASTERN AUSTRALIA: EARLY STUDIES, PHYSICAL VOLCANOLOGY, AND ERUPTION RISK

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The young volcanic regions of southeastern Australia are known as the Newer Volcanic Province, which can be divided into four main subprovinces. The Western Plains subprovince and the Mt Gambier subprovince in southeastern South Australia occupy broad plains, while the Western Uplands subprovince is the elevated east-west spine of Western Victoria, with the Great Divide running along its crest. Small areas of youthful volcanism are also found in the Eastern Uplands subprovince.

Beginning about 6-7 Ma ago, but mainly since 5 Ma, a new volcanic province formed on both the Uplands and the Plains, and nearly 400 small, monogenetic, scoria cones, maars and lava shields have been built up by Strombolian/Hawaiian eruptions. Fluid basalt flows have spread laterally around vents, often for many tens of kilometres down river valleys. Where the lava flows have blocked drainage, lakes and swamps have formed. Phreatic eruptions have deposited ash and left deep craters, often now with lakes. The study of the province began in 1836, and now, over a century and a half later, while the cause of activity still remains unexplained, future activity is believed to be likely.

Key words: volcanology, history, catalogue, dating, ages, eruption risk.

THE NEWER Volcanic Province (NVP) of southeastern Australia consists of an area of 15 000 km² of thin lava flows and limited ash deposits, with nearly 200 scoria cones (commonest in the western part of the Western Uplands) and about 200 lava volcanoes (mostly on the northern part of the Western Plains, and the eastern part of the Western Uplands) (Ollier & Joyce 1964, Joyce 1975; see Fig. 1). There are also about forty maars, which are concentrated on the southern edge of the plains, along with young scoria cones, over the axis of the underlying Tertiary basin (Ollier & Joyce, 1964). The youngest dated eruption is that of Mt Gambier in nearby southeastern South Australia, at 4000-4300 B.P. (Blackburn et al. 1982). The highest volcano is Mt Elephant, near the centre of the plains. It rises a striking 240 m above the plains to an elevation above sea level of 393 m, with a crater 90 m deep, and is similar in size to Mt Kooroocheang, the highest volcano in the Western Uplands. First identified as a volcanic area nearly 170 years ago, the NVP is now one of the best studied of the world's many young basaltic monogenetic lava fields.

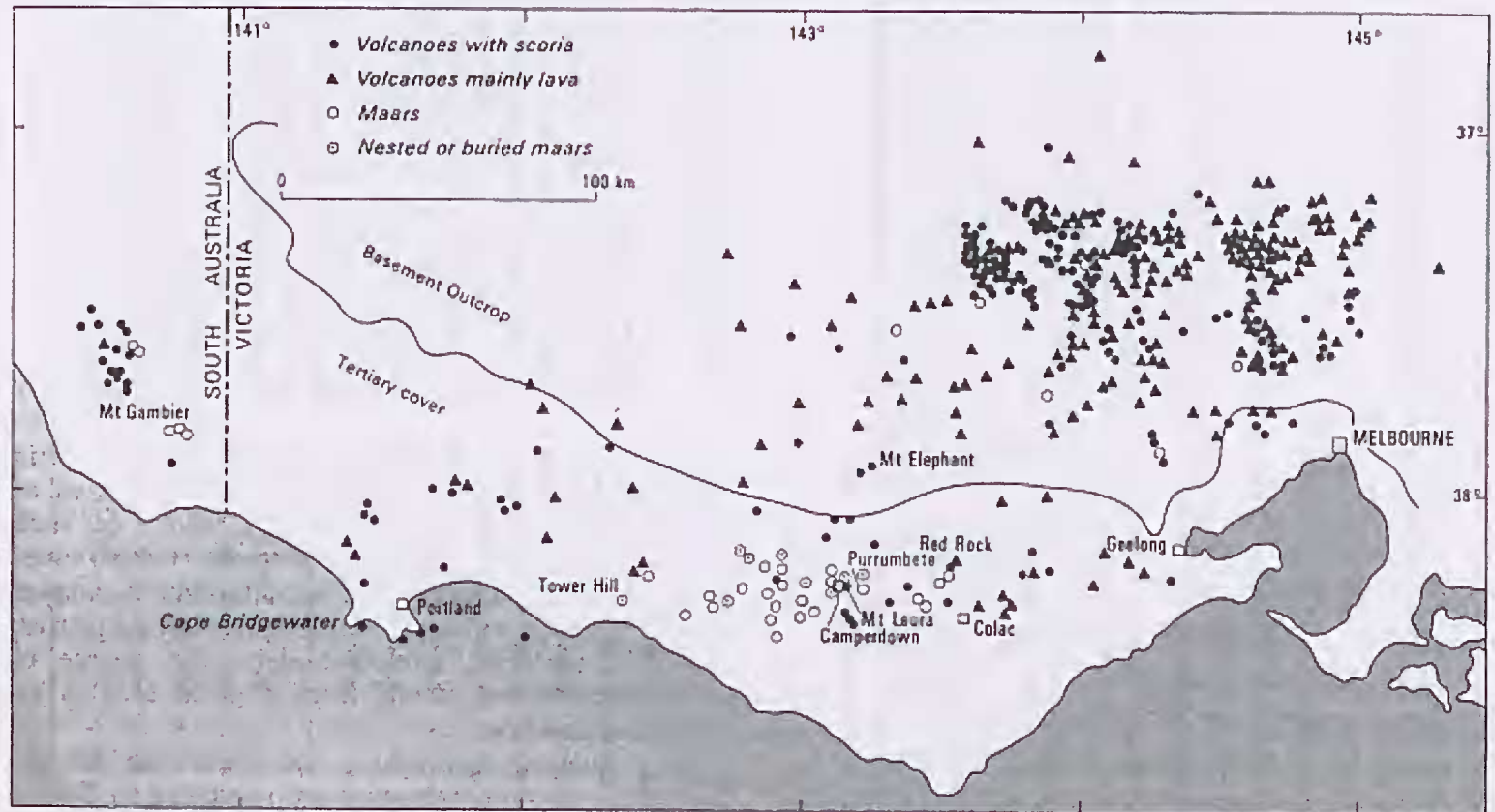
RECOGNITION AND EARLY STUDY OF THE NEWER VOLCANIC PROVINCE

Quaternary volcanism has left well-preserved cones, craters and crater lakes, scoria with iridescence, and stony rise lava flows with ropy and glassy surface textures - in fact such an obvious youthful appearance overall that in 1836 the explorer Major Mitchell, who was the first person to recognise the area as volcanic, suggested that eruption had been "within the memory of man". Mitchell (1838) provided the first written description of the Western Plains "We now travelled over a country quite open, slightly undulating and well-covered with grass...vast plains, fringed with forests and embellished with lakes ...the open plains extended as far as the eye could reach..." Mitchell had no difficulty in identifying volcanic cones, craters and lava flows (see further discussion in Branagan 1989).

Tyers (1840) described the Plains region following his government surveying expedition, and soon the volcanic nature of the NVP became well known locally.

VOLCANIC TIME-SPACE RELATIONSHIPS

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Fig. 1. Volcanoes of the main parts of the Newer Volcanic Province by type, based on Joyce 1975 (from Johnson 1989).

Westgarth (1846) wrote the first scientific article on the region, and this was published in the *Tasmanian Journal of Natural Science*. Wathen (1853) was the first to mention the volcanic regions in an international scientific journal, the *Quarterly Journal of the Geological Society of London*, while Brough-Smyth's 1858 publication in the same journal was the first significant report in an important overseas scientific journal, and included a sketch map showing "the Positions of Extinct Volcanos" (not all accurate) as well as several geological cross-sections and a plan of Tower Hill. In 1859 Selwyn published a general account of the volcanic area, based on his early mapping in central Victoria.

Descriptions of the region in books included Westgarth (1848) and Wathen (1855). Of importance at this period was the work of Bonwick, an inspector of schools, who recorded his observations of Western Victoria and recognised, described and interpreted many of its geological features in his 1858 book. In 1866 in the *Proceedings of the recently founded Royal Society of Victoria* Bonwick compared the volcanic rocks and features of Victoria with those of the area around Rome. In 1869 Brough-Smyth produced his monumental compilation on "The Gold Fields and Mineral Districts of Victoria" in which many features of the volcanic province are described and discussed.

Working across the border in South Australia was the Reverend Julian Tenison Woods whose important book (Woods 1862) described the volcanic features of Mt Gambier and Mt Schank in detail. Woods' lectures at Portland (1865) also included discussion of volcanic features.

Perhaps most significant at this time was the summary by Selwyn and Ulrich (1866), who described the Tertiary basalts of Victoria and noted the "widespread sheets" of the Newer Volcanics and the "conical or mammaloid hills", many of which have "very perfect central crater-basins".

They distinguished two types of crater basins - those with deep freshwater lakes or shallow swampy lagoons, such as Mount Gambier and Tower Hill, and those which were dry, well-grassed and thickly timbered, such as Mount Noorat and Mount Elephant. They concluded that "most of them were subaerial volcanic vents, forming low islands in the tertiary seas, under the waters of which the lava streams flowed and were consolidated". They suggested that Purumbete, Gnotuk, Terang and Keilambete "may perhaps also have been the sites of old craters" but concluded that "many of them are accidental depres-

sions due to other causes" and compared them with the lakes of the northwest of Victoria.

Selwyn and Ulrich (1866) also included a table which listed 79 "volcanic cones and crater hills", and most of these were shown on a colour folding map at 32 miles to 1 inch (reduced from an 1863 sketch map at eight miles to one inch).

They recorded that "Extensive basaltic caves are not uncommon in the western district" and described Skipton Cave, giving the dimensions of the chambers, and noting the presence of bats and thick deposits of their excrement. Analyses of basalts, both Older Volcanic and Newer Volcanic, were also given.

Several publications of Hart (for example 1901) and by Hall (1907) led into the work of the twentieth century. These writers were largely concerned with the lavas and tuffs of the volcanic areas.

Early twentieth-century studies

J. W. Gregory, first Professor of Geology at the University of Melbourne, discussed the region in his 1903 textbook (revised in 1912). The next major study was by Grayson & Mahony (1910) who with university students mapped the Colac-Corangamite region in a report published by the Geological Survey of Victoria. They were also to make the erroneous claim, repeated many times since (see discussion in Joyce 1984) that "It is the third largest plain of its kind in the world".

Skeats (1909) reviewed information on the volcanic rocks of Victoria. Fenner (1921) described the craters and lakes of Mount Gambier in South Australia. Skeats & James (1937) described the volcanic areas of western Victoria in an article for the *Royal Society of Victoria*, developing the ideas of Mitchell and early geologists; they particularly described and discussed the stony rise flows, and the lava caves found in them, comparing what they saw with features from other volcanic areas around the world.

Hills prepared a map of the Physiographic Divisions of Victoria as part of the *Physiography of Victoria* section of Skeats (1935), and marked on the map just over 100 centres of eruption in central and western Victoria. Later Hills (1938) was successfully able to estimate the age of the volcanics using a physiographic approach. Edwards (1938) described the petrology and geochemistry of the NVP in detail. Crawford (1940), and Edwards and Crawford (1940) described the volcanic rocks of the Gisborne district.

More recent studies

E. D. Gill (1950, 1953), from the Museum of Victoria, was one of many workers who began a new phase of study in the NVP. During this period Condon (1951) described and mapped the lower Werribee River region, Coulson (1954) the Daylesford region, Yates (1954) the Ballarat district, and Hanks (1955) the plains north of Melbourne. The Geological Survey of Victoria published detailed mapping in the far western part of the NVP by Boutakoff (1963), also described by Coulson (1941).

C. D. Ollier, with Joyce and others, made a series of studies of lava eaves, flows and volcanoes in the 1960s (Ollier & Joyce 1964, Ollier & Brown 1965), and attempted to identify all points of eruption in the NVP. In 1963 Gill organised a symposium on "The Basalt Plains of Western Victoria" which was published in 1964 as volume 77 of the Proceedings of the Royal Society of Victoria, and included amongst a number of papers Gill (1964) and Ollier and Joyce (1964).

A complete catalogue of Newer Volcanic eruption points in Victoria, incorporating earlier work, was prepared in 1967 by O. P. Singleton and E. B. Joyce for an international series, but never published (Singleton and Joyce 1970). A related catalogue covered the South Australian eruption points (Walker 1967).

Since the 1970s continuing work by students at the universities of Melbourne, Monash and La Trobe has added new details, especially of the Plains volcanoes. The Singleton and Joyce (1970) catalogue remains unpublished, but has been discussed by Singleton and Joyce (1969), Ollier (1967, 1969) and Joyce (1975 and later), and many details have been incorporated into the volcanic heritage review of Rosengren (1994).

With the invention of radiocarbon dating in 1950, Gill began dating samples related to past volcanic activity from the mid-1950s, and obtained the earliest dates for the Tower Hill eruption (Gill 1967). Potassium-argon dating work by McDougall and other workers commenced in the late 1960s (McDougall et al. 1966, Aziz-ur-Rahman and McDougall 1972, Wellman and McDougall 1974). Cosmogenic and OSL dating is now helping to date the younger volcanic activity of the area (Stone et al. 1997). A recent review of dating studies is given in Graham et al. (2003).

Some controversy exists, such as the dating of Mt Gambier (see Sherwood et al. 2004) and in general a number of the younger scoria, lava flow and maar volcanoes have been found to be older than suggested by past estimates and dating. In general a period of higher activity over the last 30,000 to 50,000 is indicated for the central and western part of the Western Plains subprovince.

In other scientific studies, Irving and Green (1976) described the geochemistry and petrogenesis of the "Newer basalts" of Victoria and South Australia, followed up by later workers (see review in Graham et al. 2003). Heat flow in the Plains was assessed as higher than average by Cull (1982) but further studies (Cull 1991) have failed to support this. Hilmanysah (1985) worked on the eruption hazard of the NVP, later reviewed by Blong (1989).

Why volcanism in the NVP commenced where and when it did, and continued for so long, is still not fully understood (Duncan and McDougall 1989, Lister and Etheridge 1989). Recent reviews of the NVP include Joyce (1988), Nicholls and Joyce (1989), Cas (1989), Graham et al. (2003), and Preece et al. (2003). Birch (1994) provides a useful illustrated summary.

THE NEWER VOLCANIC PROVINCE

The Western Plains subprovince

The Western Plains consist of a major volcanic plain, often called the Western District Volcanic Plains, and a generally flat coastal plain (see Joyce et al. 2003). The latter is a depositional surface left by the final retreat of a series of Tertiary-Quaternary transgressions, and later partly modified by fluvial and aeolian erosion and deposition. This depositional surface also underlies much of lava and ash deposits of the Volcanic Plains. At depth are the Tertiary marine sediments of the Otway Basin.

The Western Plains are generally less than 200 m above sea level and are a major part of the Newer Volcanic Province of southeastern Australia. They extend from the border with South Australia in the west, as far as Melbourne in the east, and northwards to the junction of the Plains with the Western Uplands.

The youngest lava flows form 'stony rises' with a characteristic relief of up to 20 m. They have sharp boundaries, commonly stepping down onto the surrounding plain by up to 15 m, and are readily recog-

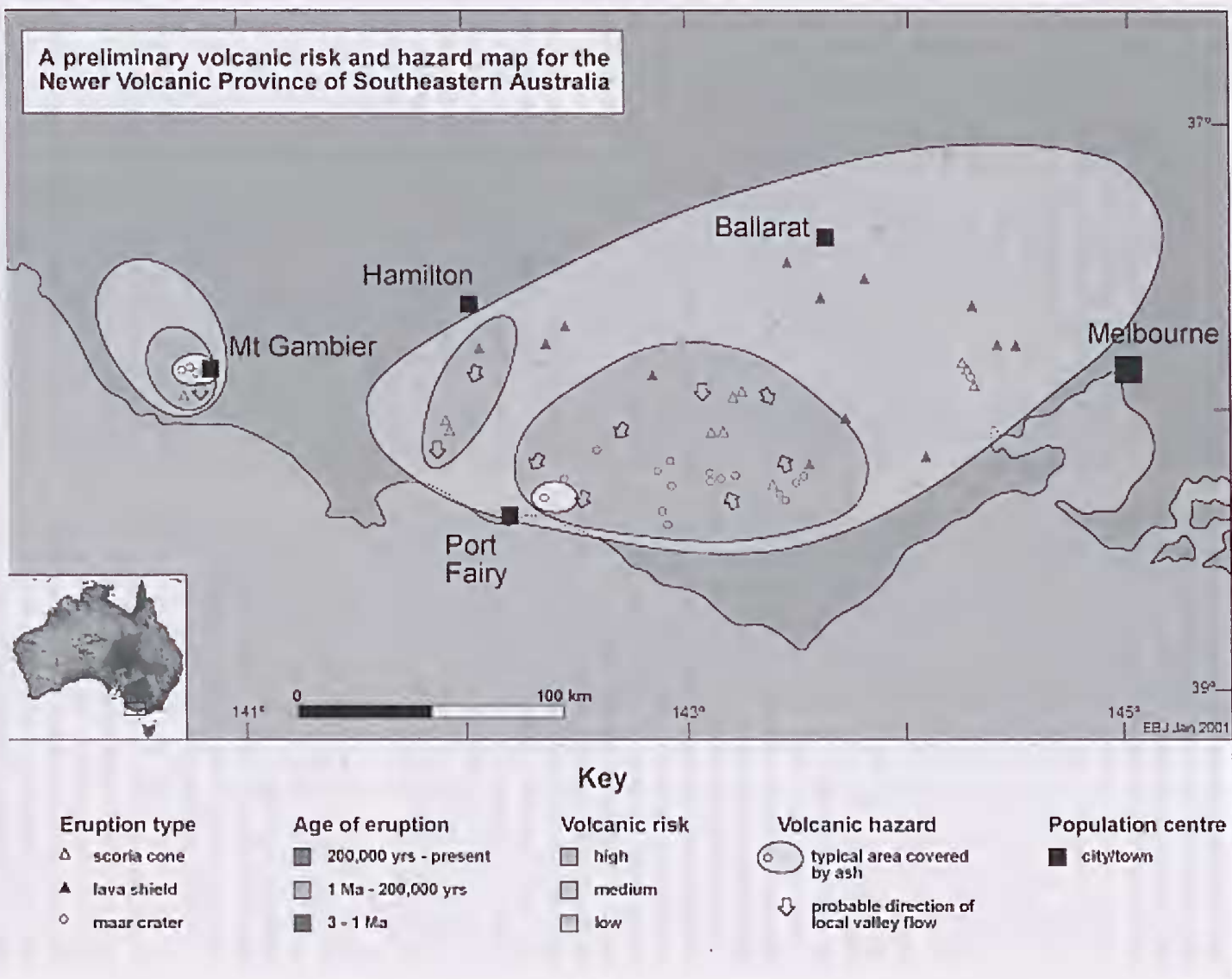


Fig. 2. Mapping of eruption types and ages with an indication of volcanic risk and hazard for the Newer Volcanic Province (Joyce 2001a).

nisable by their characteristic irregular stony surfaces, thin soils and woodland cover. These young lava flows have a shallow, brown to black clay soil through which boulders protrude on the slopes and in depressions. Basalt outcrops occur on the rises. The stony rise flows form extensive areas around individual volcanoes (e.g. Mt Eeles, Mt Napier, Mt Rouse), spreading radially as a series of lobes which overlap to build up a sheet of lava. The outbreak of tongues of liquid lava from inside the lobes and the collapse of the original surface over the evacuated area formed the irregular hummocks, ridges and sinuous or basin-like depressions of the stony rises.

Around Mount Porndon there are extensive plateau areas, with irregular collapsed areas further from the vent and distinct lobes at the outermost edge of the lava field, where the flows run out on to the floor of Lake Corangamite. K–Ar and radiocarbon dates indicate ages of less than 1 Ma for stony rise flows, and many eruptions are less than a few hundred thousand years old (Joyce 1999).

Most flows on the plains are thin, often from 2 to 10 m, and in detail consist of individual units as little as 0.5–1 m thick. Valley flows are often mappable for long distances, for example the Harman Valley flow from Mount Napier extended 20 km (Ollier & Joyce, 1973) and a valley flow from Mount Eeles travelled 50 km. Valley flows can be up to 100 m or more thick, and often composed of several distinct flows. The somewhat older subdued stony rise flows from Mount Rouse, dated at about 300,000 years, followed pre-existing valleys for 60 km to the coast (Sutalo & Joyce 2004). In each case the lava remained fluid by flowing within lava tubes in the interior of the flows.

Lava tubes or tunnels, known locally as lava caves, are a major feature of the NVP (Webb, Joyce & Stevens 1993) and the caves of the Byaduk area in the flows from Mt Napier, and the caves of the nearby Mt Eeles complex, are features of international importance (Ollier & Brown 1965, Joyce & Webb 1993).

Maar craters formed by phreatic eruptions are concentrated along the Colac–Camperdown–Warrnambool line, following the axis of the underlying Tertiary Otway Basin and reflecting the presence of groundwater in limestone aquifers at depth. A possible east–west structural control, related to the uplift of the Otway Range to the south, is shown by east–west fault scarps. The offshore volcano of Lady Julia Percy Island (Edwards et al. 2004) and the volcanoes forming the major headlands southwest of Portland, lie near the same boundary.

Volcanic ash (tephra) is not extensive in the NVP. Ash deposits, locally known as tuff or “sandstone” or sometimes “wombat”, are common in the Colac–Camperdown–Warrnambool region, coming from the maar volcanoes such as Bullenmerri and Gnotuk. Ash may extend downwind (east) from maar vents for up to 8 or 10 km, as at Tower Hill, some 33,000 years old, near Warrnambool (Sherwood 2004). Evidence from modern volcanoes elsewhere suggests thin but extensive ash deposits may also have been associated with scoria cone eruption (Blong 1989); these have presumably now weathered to soil mantles.

Crater lakes are well developed in the maars of the Colac–Camperdown area, and are commonly brackish to saline, for example Lake Keilambete, and Bullenmerri and Gnotuk (Ollier & Joyce 1973), although a few are freshwater, for example Lake Purrumbete. Studies of palaeolake level and salinity (Jones et al. 2001) ostracods (De Deckker 1982) and especially of pollen (D’Costa et al. 1989; Harle et al. 2002), have provided dating and elucidation of crater-lake histories. Tower Hill has shallow lakes which dry out at times but later reform. Several other crater lakes have become permanently dry in the 20th century, for example Lake Wangoom and Lake Terang. Lake Surprise at Mt Eeles is an unusual elongate crater lake.

The effects of basalt flows on drainage systems include the displacement of streams laterally, the ponding of streams against flow edges (e.g. Buckley’s Swamp northeast of Mt Napier), and the formation of lakes, swamps and disordered drainage on the flows themselves. In some cases, for example around Geelong, and along the course of the Curdies River south of Mount Porndon, lateral stream valleys have themselves been filled with further lava, forming further lateral streams. On much of the Plains, the low relief and continuing volcanic activity has allowed only shallow and poorly integrated drainage systems to develop, except for the major incised valleys of the Moorabool–Barwon system near Geelong, in part due to tectonic uplift, and the Hopkins – Mt Emu Creek river systems near Warrnambool and the coast; the latter, with their terraces and floodplains, are the only major drainage lines to cross the centre of the Plains and reach the coast.

Mt Clay (189 m high) is a large tuff volcano which sits on an uplifted block of Tertiary sediments northwest of Portland (Boutakoff 1963). The Staughtons Hill volcanic complex, south of Terang, consists of a maar, several broad scoria mounds and a small, spatter-rimmed crater, sitting on a block of Tertiary

sediments elevated some 60 m and now marked by solutional sinkholes (Joyce 1975). The uplift probably occurred at about the same time as the volcanic eruption.

Little seismic activity is on record for the Western Plains over the past 100 years (Gibson et al. 1981) since the major Warrnambool earthquakes of 1903 and the offshore Kingston/Beachport (South Australia) earthquake of 1897.

Mt Gambier subprovince

Separated by some 50 km from the nearest volcanoes of the Western Plains are the young volcanoes of Mt Gambier and Mt Schank (Sheard 1978, 1983). Other earlier eruption points lie on a fault-bounded block to the northwest (Fig. 1). These volcanoes overlie the Tertiary Gambier Basin, with similar subsurface geology and depositional and tectonic history to that of the Otway Basin which underlies the Western Plains of Victoria.

Domal uplift and faulting is associated in South Australia with the Mt Gambier volcanic complex, and also found in areas to the north and northwest (Joyce 1992).

The Western Uplands subprovince

The Western Uplands is an elevated region of Palaeozoic sedimentary rock and granite which extends westwards from a line running due north from Melbourne. The eruption of over 250 scoria and lava volcanoes produced valley flows and small lava plains on a previously uplifted and dissected upland (see Joyce et al. 2003). The flows filled valleys at least as deep as the present valleys, and the thickness of the lava, often more than 100 m, allowed slow cooling and the development of columnar jointing, exemplified for example at Barfold Gorge, and the Devil's Kitchen near Linton. In places continued eruption completely buried the original dissected topography to give small lava plains, for example in the Ballarat-Creswick area (Taylor et al. 2000). The largest volcano in the Uplands is Mt Kooroocheang, (also known as Mt Smcaton), north of Creswick, which rises 200 m above the plain to an elevation above sea level of 676 m. Mt Warrenheip and Mt Buninyong are large young cones near Ballarat.

The valley-filling lavas preserved underlying alluvium as "deep leads". The Campaspe lava flow is

over 85 km long, making it possibly the longest flow in Victoria (Cocciani 1999). Some deep leads contained gold, and were extensively mined in the 19th century. The mining records have allowed reconstruction of the pre-eruption drainage patterns, which are in general very similar to the present stream systems (Taylor & Gentle 2002).

Post-eruption incision at the edges of valley flows has formed deep gorges flanked by plateaus, and in places twin lateral streams have developed, such as Goodmans Creek and Pyrites Creek to the north of Bacehus Marsh, which lie on each side of the 3.48 Ma Mt Bullengarook flow, which now forms a plateau. The Guildford Plateau, southwest of Castlemaine, is another remnant of a flow with incised lateral streams. Waterfalls often develop on the edge of lava plateaus, for example Trentham Falls, Lal Lal Falls, and Turpins and Mitchells falls (near Barfold).

Near Bacehus Marsh, at the eastern margin of the Western Uplands, intermittent movement on the Rowsley Fault has produced a scarp from 90 to 270 m high and caused strong rejuvenation of the Lerderderg and Werribee rivers and Parwan Creek. This incision produced spectacular gorges in the resistant Palaeozoic sediments and granites upstream, and wide valleys in soft Tertiary sediments underlying Newer Volcanic lava flows along Parwan Creek and the lower course of the Werribee River. Lava flows dated at 4 Ma are folded monoclinally across the fault (Joyce 1975), and younger flows are warped on the nearby Lovely Banks Monocline, north of Geelong, suggesting that movement began in the late Pliocene, and probably continued into the Quaternary.

Earthquakes are associated with the Rowsley Fault, for example the ML 4.7 Balliang earthquake of 2nd December 1977. Another concentration of earthquake activity in the Western Uplands extends from Bendigo southwest towards Ballarat. Overall however, the Western Uplands area is seismically much quieter than the eastern parts of Victoria.

The Eastern Uplands subprovince

Several small areas in the Uplands of Eastern Victoria had been recognised as part of the NVP. The Morass Creek Volcanics of Hills (1938) were later dated and renamed the Uplands Province by Wellman (1974). To the north of Benambra erosional remnants of several flows extend north-south along valleys for

at least 20 km and this area has now been redescribed and further dated by Sutherland, Graham & Zwingmann (2004).

ERUPTION RISK

If activity in the NVP had been regularly spaced over time, simple arithmetic (400 volcanoes in 5 Ma) would suggest there would have been an eruption every 12,500 years. The most recent eruption which has been dated is Mt Gambier, at 4000-4300 B.P. (Blackburn et al. 1982), so on that basis we are well within the possible period for future activity.

Individual lava flows have been dated by K/Ar, radiocarbon, and other isotopic techniques. A more detailed chronosequence of lava flows, cones and craters can be built up from observed changes in landforms, drainage, soil and regolith, using field mapping, air photos and satellite imagery, and new airborne geophysical imagery (Joyce 1999). Such work is helping assign ages to otherwise undated flows, and we can see cycles of activity through time, notably a period of more concentrated activity in the late Quaternary in far Western Victoria (Joyce 2001a). Perhaps a dozen volcanoes may have erupted within the last 20,000 to 30,000 years - this would be an eruption every 2,000 years or so. However if eruptions were in clusters, as seems likely, there may have been somewhat longer periods between each cluster.

Future eruption

Australian volcanologists agree that further eruption is possible (Blong 1989), and may well be overdue. A future eruption would not be the renewal of activity at an existing volcano, but the initiation of a new volcano. The pattern of age distribution in the NVP can be used to suggest where a future eruption is most likely (Fig. 2).

Little warning of an eruption would be expected. Minor seismic activity with small earthquakes might precede the eruption by some weeks, and there could also be minor uplift or subsidence of the ground surface, and perhaps changes in ground temperature, and the exhalation of volcanic gases and steam.

The types of eruption to be expected are:

- maar crater formation with ash falls for several kilometres downwind i.e. to the east;
- cinder/scoria cone formation by fire-fountaining; and

- lava shield building and associated long valley flows.

These three types may occur separately, or in combination. For example an initial maar eruption may be followed by cone building within the maar crater (Tower Hill), or a series of lava flows and the building of a lava shield may be followed by final scoria cone formation (Mt Napier).

Activity might last for weeks or months, or for some years. If eruptions are clustered, further volcanoes, perhaps of a different type, may form near the initial eruption site, thus affecting a wider area for a longer period. Fumarolic activity and minor gas and ash eruption may continue for many years after the end of the main eruption.

Maar activity would provide particular problems from ashfall if upwind of a town or one of the major cities of the area, such as Melbourne or Ballarat. Lava flows would follow the general slope and move down pre-existing valleys (Fig. 2). Hazard impacts would include property and infrastructure damage by lava and ash fall; the effects of ash fall on people, farm animals and crops; water pollution and stream changes; grass and forest fires; and earthquakes and ground deformation. Emergency management would be concerned with evacuation planning, diversion or control of flows, removal of ash and scoria, control of fires and floods, and the repair and rebuilding of infrastructure, especially roads and bridges (see discussion in Blong 1984). A risk and hazard map (such as Joyce 2003) can suggest where a future eruption might occur (Fig. 2). To allow planning for preparedness and mitigation, eruption scenarios should be developed and publicised. Public education will be necessary, both within the local community, and for planners within local government and emergency organisations (Joyce 2001b).

Future studies

Intraplate volcanism is widespread around the world, but a major problem is explaining why such activity occurs. The detailed information now available for the NVP makes it an ideal region to attempt to solve this problem (see discussion in Price et al. 2003, Cas 1989, Johnson 1989).

The geological heritage values of the NVP are well documented (Joyce & King 1980, Joyce & Webb 1993) and can provide an important way of promoting hazard and risk concepts to the local inhabitants (Joyce 2001b). Recent threats to this heritage, which

is of national and international significance, include quarrying (Mt Leura), housing development (Lake Gnotuk, Mt Aitken) and landform destruction (Byaduk lava flow from Mt Napier). However new reserves have been developed at Mt Elephant and Mt Rouse volcanoes, and there have been recent improvements to interpretation at other sites (Mt Leura, Byaduk flow), and the development of the Volcanic Trail, a recent National Trust landscape study of the Stony Rises, and the establishment of the Volcano Discovery Centre at Penshurst, near Mt Rouse volcano, are all promising developments. In the future the integration of volcanic research, local history study, and heritage interpretation could be the key to developing a greater awareness of volcanic risk and hazard in the Newer Volcanic Province southeastern Australia.

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